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INSTITUTE REPORT NO. 31

CHARACTERISTICS OF DAMAGE PRODUCED BY NON-CIRCULAR RETINAL LASER RADIATION

NON-IONIZING RADIATION DIVISION
DEPARTMENT OF BIOMEDICAL STRESS
OCTOBER 1976

LETTERMAN ARMY INSTITUTE OF RESEARCH PRESIDIO OF SAN FRANCISCO CALIFORNIA 94129

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A comparison of the appearance of retinal burns produced by slit laser radiation was made using the same optical apparatus for argon (514.5 nm), neodymium (1060 nm), and ruby (694.3 nm) lasers. The retinal changes produced by exposures to these slit images were elongated for laser exposures less than or equal to 12 ms. For longer exposure times, the retinal opacifications were circular in appearance. A partial explanation is presented based on the thermal conductivity of the retinal tissue.

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INTRODUCTION

Research[1] which resulted in threshold data for the cooled Gallium Arsenide (GaAs) laser demonstrated a circular retinal burn response to a slit laser source. These data included precise physical evaluation of the angular distribution of the laser beam. In all cases, the far field pattern was a slit. Studies made of the retinal pathology[2] demonstrated circular burns with central sparing.

Within the past year the Army has developed increasing interest in the GaAs laser and the definition of hazard levels for this laser. In order to further investigate the GaAs results, this study was undertaken to answer some of the questions of retinal tissue response to modified beam characteristics. The experiment was designed to determine the appearance and dimensions of the retinal lesions produced when the irradiated area is a vertically elongated rectangle. Various exposure durations and wavelengths were evaluated with argon, ruby, and neodymium laser systems. These conditions allowed comparisions of wavelength and exposure duration effects.

EXPERIMENTAL APPARATUS

An optical system was devised to transform laser output into a beam having a well defined rectangular far field pattern (Figure 1). Crossed cylindrical lenses concentrated the laser beam through a slit onto a finely ground glass surface. This lens combination had a greater power in the horizontal plane than in the vertical, yielding a focal energy distribution partially forming a vertical slit. The power of the lenses was dictated by the requirement that the focal irradiance stay below the damage level of the slit and diffuser material. It was necessary to closely approach that damage level in order to transmit sufficient energy to perform this experiment. A simple lens recollimated the diffusely transmitted radiation. An aperture limited the beam to ocular pupil size (7 mm), and a beam splitter diverted the beam into the animal eye while allowing direct observation by use of a fundus camera.

The divergence of the beam was determined by the dimensions of the slit and the focal length of the collimating lens. The slit width, adjusted to the minimum that would transmit sufficient energy to perform the experiment, determined the horizontal beam divergence. The slit

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[1]Lund, D. J., et al., Army Science Conference Proceedings, Vol. II, pp. 323, 1972.

[2]Adams, D. O., et al., Invest Ophthalmol, 1(6):776, 1962.

height was greater than the irradiated area which, therefore, determined the beam divergence in the vertical plane. The collimating lens had a focal length of 21.8 mm, while the slit dimensions were approximately 0.1 mm x 0.6 mm corresponding to beam divergences of 5 mrad x 30 mrad. Exact values for each laser tested are listed in the tables.

The far field pattern (Figure 2) as obtained at the focal plane of a one meter lens, was a sharply defined rectangle. The diffusing glass used in conjunction with the slit was found to be essential. Without it, the far field image exhibited the Franhoffer diffraction normally obtained when coherent monochromatic radiation passes through a slit. The diffuse surface negated diffraction by scrambling spatial coherence.

The identical components and configuration were used with each of the lasers evaluated in this study. Minor adjustments of lens position and slit width corrected for wavelength effects and transmitted energy requirements.

PROCEDURE

The animals used in these experiments were rhesus monkeys (Macaca Mulatta) weighing between 2 and 5 kg. Preanesthetic medication consisted of a sedative dose of phencyclidine hydrochloride (0.25 mg/kg) injected intramuscularly and atropine sulfate (0.2 mg) subcutaneously. Anesthesia was induced with sodium pentabarbital (approximately 5 mg/kg) via the saphenous vein. A pediatric intravenous injection set was placed into the saphenous vein to administer fluids and to facilitate additional anesthetic. The pupils were dilated with phenylephrine hydrochloride (10%) combined with tropicamide (1%). Sutures of 6-0 silk were placed in the upper eyelids to facilitate manipulation. While the eyes were open during the experiment, physiologic saline was used to maintain corneal transparency.

The animals were positioned in the exposure system and the fundus examined via fundus camera. Several exposures were placed beginning at levels producing immediate retinal opacity and decreasing to levels producing minimal opacity. The macular area was exposed last at the minimal opacity level. This central optical area was selected because of its increased contrast visibility and the superior optical quality along the axis of the eye, both of which tend to maximize the fidelity of production and examination of retinal lesions. Detailed ophthalmoscopic examination was conducted at intervals from 1 to 5 days post exposure. All animals were sacrificed and the retinas prepared for study via flat preparation.

RESULTS

Animals were exposed to four separate laser wavelengths chosen to evaluate exposure duration and wavelength dependency. The results are tabulated in Tables I-IV and Figure 2.

DISCUSSION

The experiment was designed to evaluate the effect of exposure duration and wavelength on retinal response to slit geometry irradiation. Comparing similar wavelengths, Q-switched Nd and cw Nd (1060 nm), the wavelength, delivery system, slit aspect ration (defined as the slit height divided by the slit width), animal preparation, and ocular refraction were held constant. Q-switched exposures produced elongated burns while cw (milliseconds to seconds) exposures produced round burns for all exposure durations tested. A series of corrective lenses to refocus the 1060 nm laser failed to result in slit burns for the cw exposures. The shortest cw exposure was limited to 38 msec by available laser power. This result is, in part, consistent with thermal damage models which assume the retinal thermal relaxation time to be short compared to cw exposures larger than a few milliseconds. At above threshold exposures, light energy is for the most part converted to heat. The retinal irradiated area becomes a thermal line source having a Gaussian distribution along its length. Thermal relaxation (heat flow and temperature elevation) occurs in a lateral direction, and the resulting burn will be widened in that dimension (ellipsoidal to round). Thermal relaxation for the Q-switched exposures is less important in that the tissue time-temperature history occurs after completion of the energy deposition on the tissue, and the maximum temperature profile corresponds closely to the irradiated area. In addition, thermal processes may be less important in the mechanism of damage for nanosecond exposure durations.

With Q-switched ruby (694.3 nm) and cw argon (514.5 nm), a similar result is obtained. The Q-switched ruby exposures consistently produced elongated lesions. The cw argon produced elongated burns only for near threshold exposures of 12 msec duration, the shortest exposure resulting in damage. These argon burns show only slight elongation, consistent with thermal conduction from a line source.

The difference between the Q-switched Nd (1060 nm) and Q-switched ruby (694.3 nm) were the laser wavelength, optical focus, and retinal absorption. All other variables were held constant. Most exposures yielded elongated burns for both lasers. The ruby exposures produced

better defined slit-like lesions than the Nd. A probable cause was the more accurate focus of the eye in the visible. Further, the primary locus of Nd absorption and subsequent pathology occurs in the deeper layers of the retina and choroid contrasted to strictly retinal changes for ruby exposures. This, in the near IR, effects both the input energy distribution and the ability of the observer to detect the lesion.

The exposure time for the production of slit-like retinal lesions appears to be a critical variable. The times greater than 12 msecs result in retinal burns which more nearly approximate the characteristics of a typical circular laser exposure. At nanosecond exposure durations, the retinal opacity is vertically elongated presenting a near image of the slit-like laser energy distribution.

There was throughout this exposure series an absence of the annular burn pattern seen by direct observation for the gallium arsenide laser. A similar near IR wavelength, neodymium (1060 nm), produced round uniform burns for long exposures, 33 msecs to one second. The nanosecond neodymium exposures produced slit-like vertical retinal burns. The comparison would suggest that the gallium arsenide laser, operated in prior experiments at 120 KHz, generated a retinal tissue response similar to cw exposures for both neodymium and argon.

At 120 KHz, a one second exposure results in 120,000 individual laser exposures with minimal time to allow the retinal tissue to return to body temperature. The result is a progressive temperature increase during the exposure leading to coagulation of retinal protein. Although the term continuous wave (cw) is applied to the argon and continuous wave neodymium lasers, each exposure consisted of a series of time distributed pulses at frequencies of 2 to 3 GHz.

The Q-switched pulses for ruby and neodymium result in a single pulse on the order of 20×10^{-9} seconds. In these exposures, the retinal temperature changes occur after the laser exposure is complete and are a result of both the conversion of photon energy to heat by the melanin in the pigment epithelium as well as possible mechanical rupture of cell structures.

Five additional variables may account for the tissue response differences. Near IR wavelengths have greater transmission through the retina and pigment epithelium into the underlying choroid. For neodymium and gallium arsenide exposures, the visible retinal opacity is "deeper" and more diffuse than for argon and ruby exposures. The focal length of the optics of the eye is a function of wavelength. Routine refraction is

accomplished by clinical techniques which assume ± 0.25 diopter error as within reasonable limits. Since this error function produces a 0.5 percent change in focus, the site of laser image will be shifted. Refraction of primate eyes is accomplished by means of a white light, broadbanded source. Calculated corrections for specific wavelengths are added, but monochromatic in vivo corrections are not made.

The absorption spectra of the ocular media is a function of wavelength[3]. The transmission may vary from 70-72 percent in the 400 to 700 nm band to 40-42 percent in the near infrared 700 to 1000 ns. The retinal image may be blurred (wavelength dependent) by near axis forward scatter of light by the ocular media. The subtle curvature of the cornea which changes off the central axis may produce artifacts in the retinal image.

Each of these variables has produced some degree of alteration in the retinal image for each of the wavelengths tested. None of these factors is solely implicated at the 850 nm gallium arsenide wavelength.

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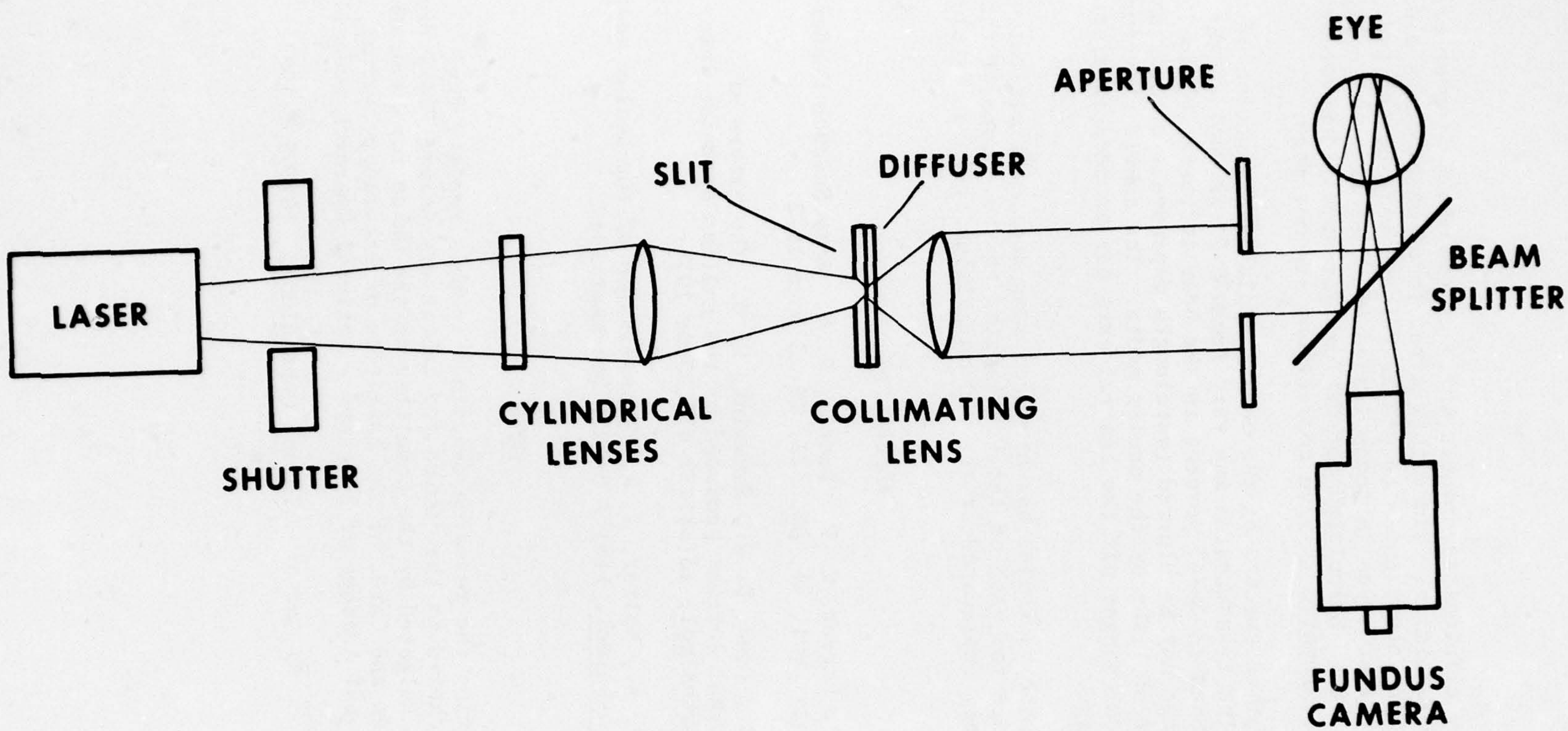
NOTE

"In conducting the research described in this report, the investigators adhered to the 'Guide for Laboratory Animal Facilities and Care' as promulgated by the Committee on the Guide for Laboratory Animal Facilities and Care, of the Institute of Laboratory Animal Resources, National Academy of Sciences - National Research Council."

[3] Boettner, E. A., et al., Invest Ophthalmol, 1(6):776, 1962.



SCHEMATIC DIAGRAM OF OPTICAL
CONFIGURATION

FIGURE 2

Far Field Distribution of Ruby Laser Beam
Modified to Produce a Slit Image

Top image was obtained with the diffuser in the optical system.

Bottom image, exhibiting Fraunhoffer diffraction, was obtained without the diffuser.

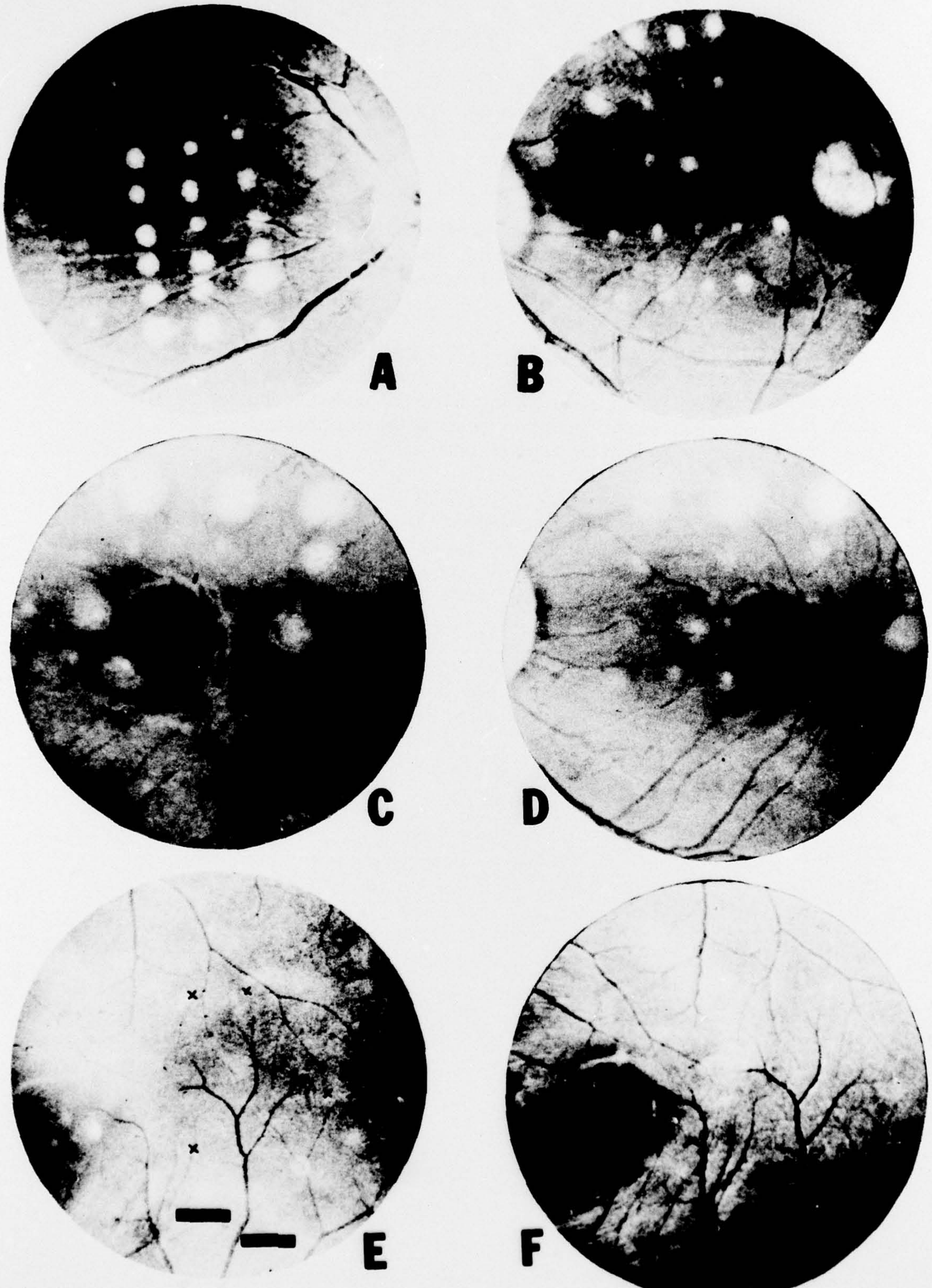

A
B
C
D
E
F

FIGURE 3

Fundus Photographs of Rhesus Monkey
Retina After Various Laser Exposures

Top (A & B) - 250 msecs neodymium (1060 nm) exposures three days after exposure. Note round uniform retinal burns in all grid areas.

Middle (C & D) - argon (514.5 nm) 13 msecs. C - one hour post exposure. D - four days post exposure. Note elongated appearance of four macular burns. Numberous round burns can be seen for longer exposure duration (upper rows).

Lower (E & F) - Ruby, Q-switched (20 x 10^{-9} seconds). E - acute (one hour post exposures). Note slit-like burns (to left of X indications). F - 20 days post exposure. Note slit-like macular burns.

Two round burns (bars) are the result of defocussing the retinal image.

TABLE I

Laser	Q-Switched Ruby
Wavelength	694.3 nm
Beam Divergence	3.5 x 30 mrad
Anticipated Retinal Geometry	60 μ x 420 μ
Exposure Duration	30 nsec
Number of Exposures	22
Number of Lesions	22
Appearance of Lesions	Elongated

Note: Thirteen additional exposures were placed. The incident beam was purposely defocussed in these exposures by insertion of lenses in the range -4 diopter to +4 diopter. All defocussed exposures produced rounded burns. See Figure 3.

TABLE II

Laser	Q-Switched Nd
Wavelength	1060 nm
Beam Divergence	5 x 25 mrad
Anticipated Retinal Geometry	85 μ x 420 μ
Exposure Duration	30 nsec
Number of Exposures	10
Number of Lesions	10
Appearance of Lesions	Elongated

Note: A total of 34 exposures was made. After the first 24 exposures it was noted that the slit was damaged, and beam geometry was not slit like. These data were excluded from consideration.

TABLE III

Laser	CW Nd			
Wavelength	1060 nm			
Beam Divergence	4.5 x 32 mrad			
Anticipated Retinal Geometry	76 μ x 420 μ			
Exposure Duration	1 sec	250 msec	70 msec	38 msec
Number of Exposures	19	46	10	5
Number of Lesions	19	46	10	5
Appearance of Lesions	Round	Round	Round	Round

Note: Exposure times less than 38 msec were not possible because the laser power was insufficient to produce opacity.

TABLE IV

Laser	Argon			
Wavelength	514.4 nm			
Beam Divergence	3.5 x 30 mrad			
Anticipated Retinal Geometry	60 μ x 420 μ			
Exposure Duration	1 sec	38 msec	21 msec	12 msec
Number of Exposures	15	2	1	15
Number of Lesions	15	2	1	15
Appearance of Lesions	Round	Round	Round	4 Elongated 11 Round

Exposure Duration	1 msec	.4 msec
Number of Exposures	7	10
Number of Lesions	1	0
Appearance of Lesions	Elongated	

Note: Slit burns occurred for near threshold macular 12 msec exposures. Minimal elongation was evident at longer exposure durations. The slit like appearance was much more obvious at 4 days than at one hour post exposure.

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